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# Effect of X-ray Computed Tomography Magnification on Surface Morphology Investigation of Additive Manufacturing Surfaces

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## Abstract

Additive manufacturing (AM) in the last decade has become a widespread manufacturing process. The possibilities that such technologies have provided for manufacturing of complex geometries compared to conventional manufacturing processes has made them popular in many branches of industry. Despite the advantages of these methods, there are limiting issues which needs to be thoroughly investigated. A limiting factor, especially for powder bed AM parts is their undesired surface finish. AM surfaces can be investigated using various methods such as optical or tactile methods, however for complex AM surfaces they are incapable of capturing all details such as deep valleys at surface level. X-ray computed tomography (CT), can provide 3D information of complex AM surfaces and does not have limitations that line of sight and tactile methods have. There are several parameters in CT investigation, which can potentially alter the obtained results. Depending on the CT magnification at which the data is acquired the result specifically surface level detail might be affected. The aim of this study is to investigate the effect of different CT magnifications on surface texture measurement of additively manufactured surfaces. Surface features, including highest peaks and deepest valleys contributing to maximum and minimum thickness of specimen from different magnifications were compared with each other. The result shows that, the lower magnification scans underestimate both peak and valley measurements in comparison to the highest magnification scan. Measurement of valleys and re-entrant features were underestimated at more considerable level. The results from this study provide some understanding regarding surface morphology assessment of AM parts and the level of detail which can be expected depending on the CT magnification.

**Keywords:** Computed tomography, Additive manufacturing, Surface texture

## 1 Introduction

AM technologies enables fabrication of near net shape parts specifically parts with complex geometries. Although, these technologies were initially used for fabrication of prototypes, nowadays they are being used for part fabrication in different branches of industry such as aerospace, automotive and biomedicine [1],[2]. Apart from the advantages of AM technologies, there are limiting factors which hinders widespread application of them [2]. One of these factors is the rough surfaces of final parts which has remained a major limiting issue in powder bed and blown powder AM methods [3], [4]. Structural response such as strength and fatigue performance of parts especially those with miniature features like lattice or thin-wall structures can be affected due to surface texture [5],[6]. Permeability or heat transfer performance of parts where a fluid is contact with AM surface such as parts with internal cooling channels or lattice structures may also alter due to surface texture of an AM part [7],[8]. The surface morphology of additively manufactured parts has been investigated using various methods in different studies. AM surfaces were investigated using non-contact methods such as optical profilometry and confocal microscopy, which are based on line of sight method in which the reflected light from the surface is recorded[9],[10]. There has been efforts to study AM surfaces using contact method in which a mechanical probe touches the surface and the height and depth of peaks and valleys are recorded. Due to complex surface morphology of AM parts which is mainly result of partially attached powder particles as well as deep re-entrant features and valleys, the line of sight and contact methods are not suitable methods for accurate surface characterization of AM parts. High resolution X-ray computed tomography, however has the potential for inspection of AM surfaces including re-entrants and valleys. Kerckhofs et al. have used CT for surface roughness measurement of AM porous material as opposed to optical and contact profiling systems while the main focus of their work was investigating the effect of micro-CT parameters on surface roughness measurement results [11]. Effect of spatial CT image resolution on surface complexity of open porous structure was studied by Pyka et al. [12],[13]. Townsend et al. have investigated AM surfaces using data obtained from CT analysis and used areal surface texture parameters in their studies [14],[15]. A limiting factor for achieving smaller voxel size and consequently higher resolution, is the size of object to be scanned. Therefore the amount of data loss or inaccuracy in measurement at surface level for AM parts which have to be scanned at lower magnifications due to size barrier, is of interest in industry. In this study, the effect of CT magnifications on surface texture measurement of a thin-walled Al10SiMg specimen fabricated using selective laser melting (SLM), has been investigated. In order to determine the level of inaccuracy in measurements, features including highest peaks and valleys were chosen as selected regions for comparison of results from different magnifications.

## 1.1 Materials and Methods

### 1.1.1 Specimen

The specimen which was investigated in this study was fabricated using selective laser melting in EOS M290, using the AlSi10Mg material. It was designed as a rectangular wall supported with a thin cylinder. The rectangular part had the thickness and height of 1.2 mm and 35 mm respectively. It was enclosed in a cylinder with a diameter of  $\varnothing 6$  mm with a wall thickness of 0.4 mm. The build direction of the specimen was along the z-direction of the AM build chamber. *Figure 1a* and *b* show the CAD design and as built geometry of the specimen. In order to remove the remaining powder particles on the surface, the surfaces of specimen were cleaned using high pressure air.

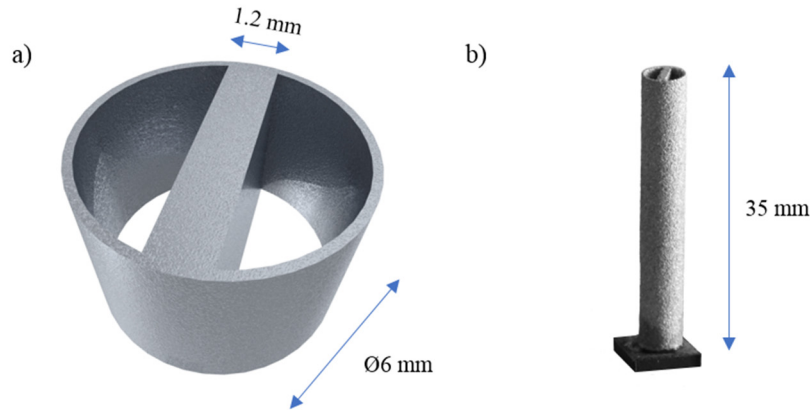


Figure 1: a) A section from CAD design of the specimen b) as-built specimen

### 1.1.2 CT data acquisition

The specimen was scanned at three different magnifications, resulting in three different data sets with voxel sizes of 7, 14, and 21  $\mu\text{m}$ . The scans were acquired using a XRADIA XRM 410 system with a tungsten target. The sample remained untouched apart from the translational movement in order to achieve the aforementioned voxel sizes. The scan settings remained the same for all the scans which are listed in the *table 1*. The volumes were then reconstructed using filtered back projection method and further analysed using the commercially available software VGStudio MAX3. ISO 50 as surface determination method was used for all the data sets.

Table 1) CT scan parameters

	High magnification scan	medium magnification scan	low magnification scan
Tube voltage (Kev)	80	80	80
Current ( $\mu\text{A}$ )	125	125	125
Number of projections	1600	1600	1600
Resulting voxel size ( $\mu\text{m}$ )	7	14	21
Surface determination method	ISO 50	ISO 50	ISO 50

### 1.1.3 Analysis method

After surface determination process, the data sets were fitted on top of each other using VGStudio MAX3, in order to further achieve same coordinate system for all of them. A 4 by 4 mm region of interest (ROI) was cut at the centre of rectangular wall of specimen from each data set. A plane using “least square method” was created by picking 200 points at surface of high magnification data set. This plane then was used for defining an axis in the coordinate system which was further used for comparison of high magnification data set with medium and low magnification data sets. Two planes parallel to the aforementioned plane were generated in order to define a measurement region. The upper boundary was the plane passing the highest peak and the lower boundary was the plane passing the deepest valley of high magnification data set. The upper boundary plane then was used as absolute zero or “reference plane for valley measurements”. The lower boundary was used as absolute zero or “reference plane for peak measurements”. The region between these two planes was called “surface region” and the measurements for comparison of data sets were performed in this region using the aforementioned planes as boundaries. Surface features, including peaks and valleys were selected as measurement items. A selection window of seventy by seventy  $\mu\text{m}$  was used to pick regions with features including 20 highest peaks as well as 20 deepest valleys. The comparison and study of measurement deviations then is performed at these selected regions.

## 2 Results and Discussion

### 2.1 qualitative comparison

Considering the obtained results from reconstructed data sets it can be perceived that, the level of magnification affects the obtained surface details of AM parts. *Figure 2a, b and c* illustrates surface texture of specimen obtained at the different magnifications at ROIs obtained from high, medium and low magnification respectively. As it is illustrated, a significant amount of detail at the surface is lost as the magnification has decreased. *Figure 2d, e and f* which belong to high, medium and low magnifications respectively, show a selected region at ROIs and how the surface features have altered due to change of magnification. As it is illustrated, the small loosely attached powder particles in medium magnification (*figure 2e*) scan are not as well captured as they are in high magnification (*figure 2d*) and they are faded out or merged to other surface feature in data set acquired from lowest magnification (*figure 2f*).

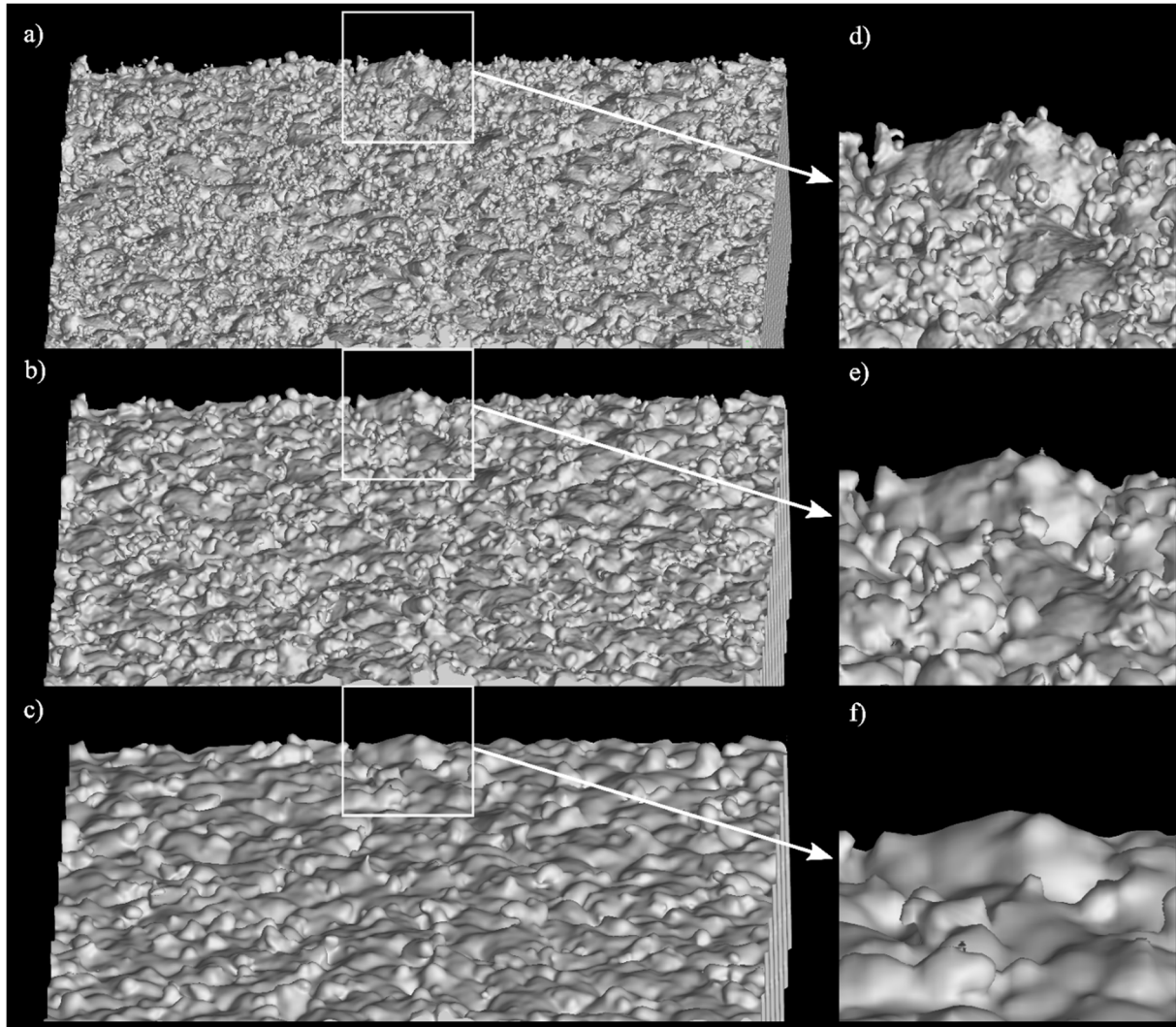


Figure 2: a), b) and c) 3D reconstructed CT volumes at ROI, displaying the surface of the specimen obtained from data sets with voxel sizes of 7, 14, and 21  $\mu\text{m}$  respectively d), e) and f) A selected region showing more details from data sets with voxel sizes of 7, 14, and 21  $\mu\text{m}$  respectively

*Figure 3a-i* are obtained at a cross-section of the specimen at ROI showing ISO surface from different magnification settings. The red line represents the ISO surface line, while the gray lines are result of ISO surface from the other two data sets. *Fig3 a, b and c* illustrate a selected region at a deep valley showing how the valley is captured at high, medium and low magnification respectively and how it is underestimated in low magnification data set. *Fig3 d, e and f* show the general view of a cross-section of the specimen. As it is shown, the high magnification data sets has captured the most detail at surface level, including the re-entrant features as well as partially attached powder particles. Such features are captured at medium magnification data set too, however the details of features are smoothed out resulting in less accurate surface texture result. At low magnification data set there are features like valleys or re-entrants that are not captured at all and considered as a part of the specimen. The parts of surface with no significant high peak or deep valleys were not affected as much as parts with features and were slightly overestimated in most cases in low magnification data set compared to high magnification data set. *Fig3 g, h and i* which are



obtained from high, medium and low magnification respectively, compare a selected region at a peak showing how differently the peak is captured at the mentioned magnifications.

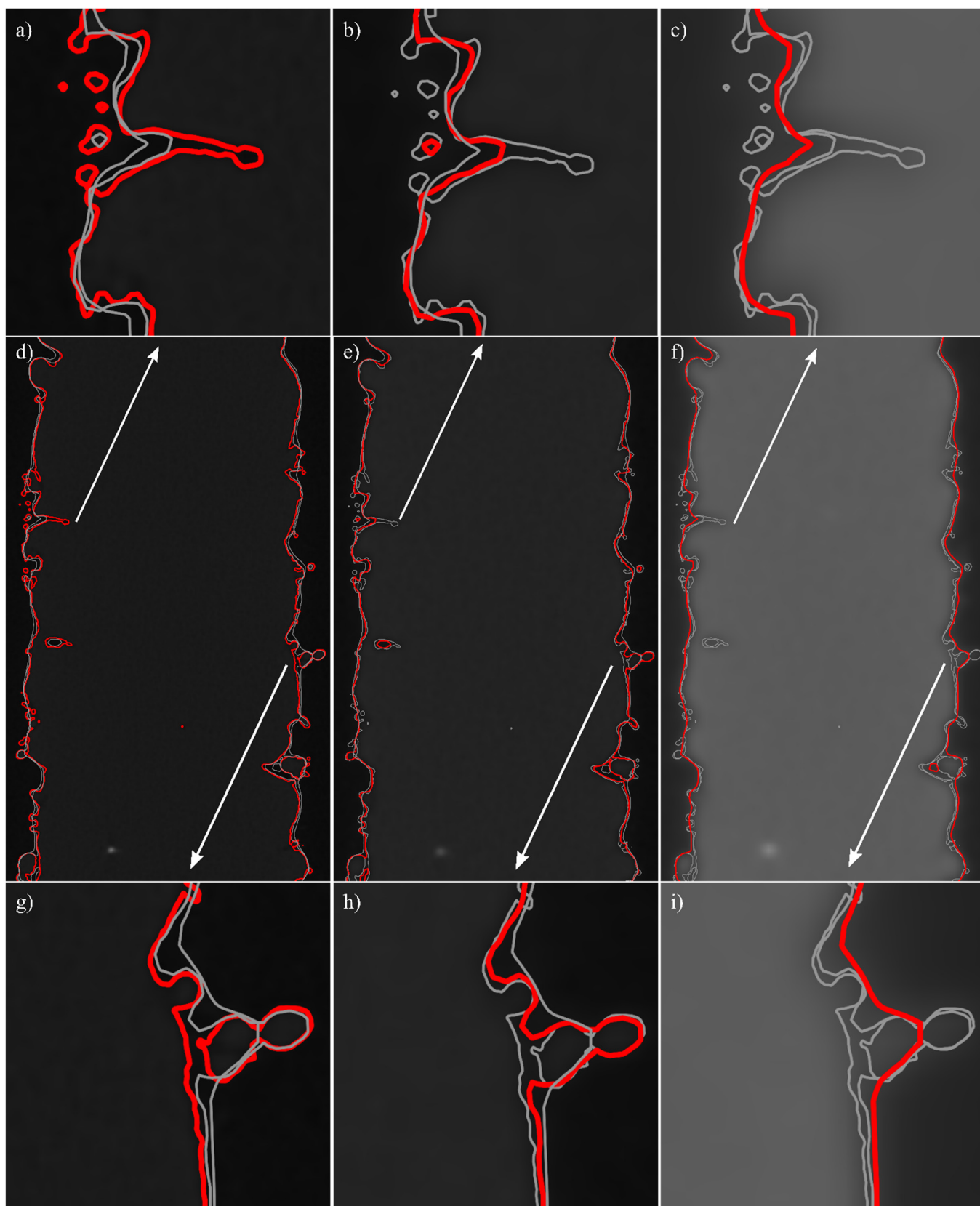


Figure3 a), b), and c) A selected region showing a valley and resulting ISO surfaces obtained at high, medium and low magnifications respectively d), e) and f) A cross-section of the specimen obtained at high, medium and low magnifications respectively and the ISO surface g), h) and i) A selected region showing a peak and resulting ISO surfaces obtained at high, medium and low magnifications respectively

## 2.2 Quantitative comparison

The data sets at the ROI, were compared to each other based on the surface features such as peaks and valleys. Regions with twenty highest peaks and twenty deepest valleys at the centre of the ROI were selected. For measurement of highest peaks at each data set in the selected regions, the maximum distance of each peak from the “reference plane for peak measurements” as percentage of “surface region” thickness is measured. Same measurement was performed for valleys by measuring their maximum distance from “reference plane for valley measurements” at each data set in the selected regions. The results are presented in *figure 4* and *figure 5*.

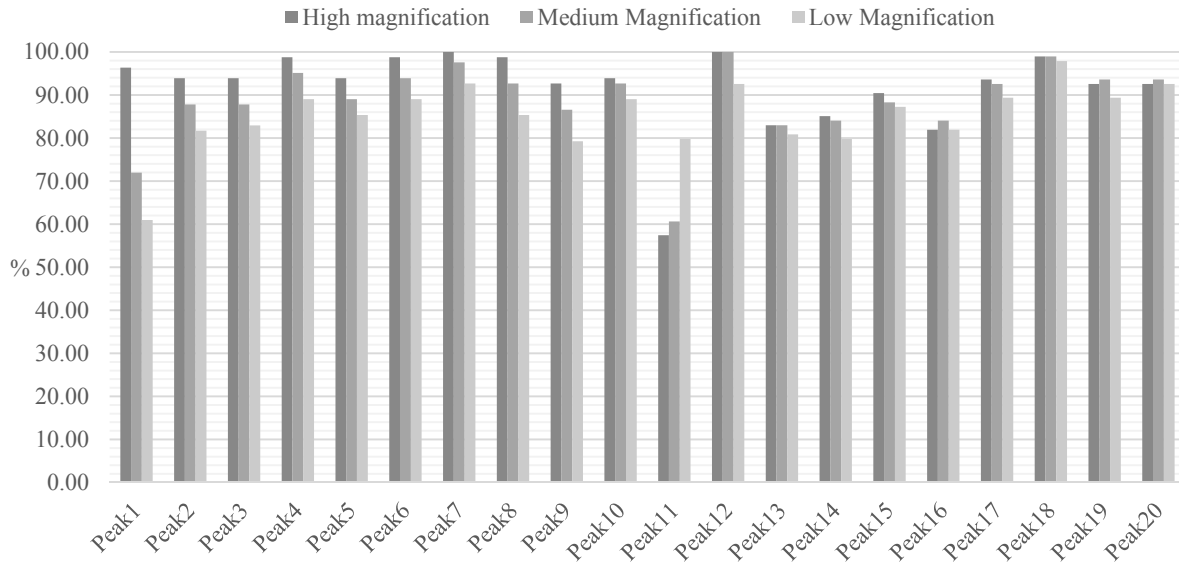


Figure 4) Measurement of peaks heights from “reference plane for peak measurement” as percentage of surface region thickness

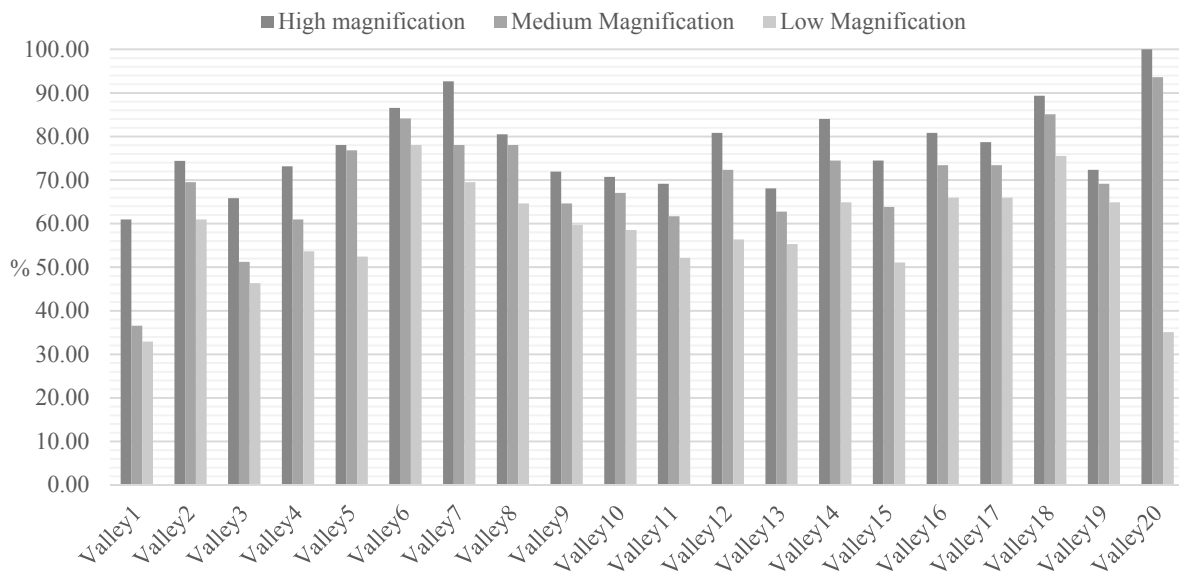


Figure 5) Measurement of valleys depths from “reference plane for valley measurement” as percentage of surface region thickness

The results from peak and valley measurement shows that surface texture measurement of AM parts is highly dependent on the magnification at which the data is acquired. As it is illustrated in *figure 4*, considering the high magnification data set as the ground truth, the medium and low magnification data sets measure equal or less values for peak measurements. Although at a few measuring point the obtained results are very close to each other, there is a peak at which the low magnification data set underestimate the peak measurements by 35% of surface region thickness. In addition, as it was expected, the medium magnification data sets in most of cases results in measurement values between measured values from high and low magnification data sets. The same observation can be seen for measurement of valleys considering *figure 5*, meaning that medium and low

magnification data sets result in an underestimated measurement of valleys in comparison to high magnification data set. The measurement difference for valleys between different data sets were considerably bigger compared to measurement difference for peaks. While for peak measurements there were many peaks which both low and high magnification data sets could measure with slight measurement difference, in valley measurements, the low magnification data set resulted in significantly underestimated values. Considering peak 11 as an outlier, the difference in measured value for high and low magnification data sets for peak measurement was between 0 and 35% and it was between 7.5 and 65% in valley measurements respectively. The medium magnification data sets results were always between high and low magnification even though at some valleys it resulted in closer measurements to high magnification and in other valleys close to low magnification data set.

The close results for the peak measurement is result of overestimation in surface determination of low magnification scan as it was shown in *figure 3f*. Another observation from *figure 4* and *5* is that, considering the high magnification scan, all peaks except one were measured in almost same level meaning that the 20 highest peaks were close to the highest peak and were measured in the outermost 20% of surface region; however the valleys were mostly measured within the first 80 % of the surface region and eight deepest valleys were measured at deeper distance from surface.

The maximum and minimum thicknesses of the specimen at the ROI, which are respectively result of peak to peak and valley to valley measurements, also showed the effect of magnification level on thickness measurement of AM thin-walled structures. The maximum thickness value for medium and low magnification data sets were underestimated 0.5 % and 2% respectively. The minimum thickness values on the other hand were overestimated even at more considerable level by measuring 8.5% and 18.5% more than measured value obtained from the high magnification data set.

The obtained results in this study were highly dependent on the surface determination method. In order to make the study repeatable and perform a fair comparison procedure, the same surface determination method was used for all the data sets. Using manual surface determination based on gray values of material and background, one could obviously achieve results closer to results obtained from high magnification data set, however this was considered operator dependent and not repeatable.

### 3 Conclusions

In this study, the effect of CT magnification as an influential data acquisition parameter, on surface texture measurement of AM surfaces was investigated. It was found that the level of surface detail drops significantly as the magnification is decreased which consequently resulted in loss of surface texture information. Since the loss of information due to magnification change affects the thickness measurement of miniature AM structures, an in-depth quantitative comparison method at surface level was carried out. Although, measurement of peaks heights showed relatively small difference at different magnifications, measurement of valleys depths were highly underestimated at lower magnification compared to high magnification data set. This resulted in fairly similar measurement of maximum thickness at all magnification levels; however it resulted in a considerable overestimation of minimum thickness obtained from low magnification compared to high magnification data set. Basically using the same surface determination method, a low magnification data set is incapable of capturing deep valleys at surface level. The result from this study provides useful information regarding measurement inaccuracy at surface level of AM parts depending on selected CT magnification. Effect of application of other surface determination methods as well as other scanning parameters can be investigated as future work.

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